On behalf of the ESA Astronomical Lunar Observatory Topical Team

MARC KLEIN WOLT, LEON KOOPMANS, CHRISTIAAN BRINKERINK, ALBERT-JAN BOONSTRA, MARK RUITER, LEONID GURVITS, DAVID PRINSLOO, HARISH VEDANTHAM, MICHEL ARTS, BORJA GUTIERREZ, JESSICA GRENOUILLEAU, JAN TAUBER

ASTRONOMICAL LUNAR OBSERVATORY

Radboud University

- MEASUREMENT OF GLOBAL 21-CM EMISSION: CONSTRAINING COSMOLOGICAL THEORIES
- DIRECTLY PROBING THE FORMATION HISTORY OF THE PRISTINE UNIVERSE
- FAR SIDE RADIO INTERFEROMETER: OPENING UP THE LAST VIRTUALLY UNEXPLORED FREQUENCY REGIME
- SYNERGY WITH HUMAN LUNAR EXPLORATION
- INTERNATIONAL LUNAR OBSERVATORY
- BUILDING ON- AND EXTENDING ON EUROPEAN HERITAGE

DISCOVERY MISSION FOR THE DARK AGES AND COSMIC DAWN


TERRAE NOVAE 2030+
Long-term strategy @Moon
esa
Cis-lunar access
ISS partnership extension
Orion's European Service Modules
Gateway's I-HAB and ESPRIT modules
Gateway astronaut flights
Gateway science
Surface access
Comms/nav services
Logistics and cargo
Comms/nav services
Collaborative science
Science on the Moon
Technical capabilities
Secure comms
In-space transportation
Redundancy
Mars transit demo
Sustainable access
Surface mobility
Support for base camp
Dissimilar redundancy
Extend "range" of science
Leverage expertise
Surface infrastructure
Power and resource provision
Extend missions duration (night survival)
Enable sustainability
Contributions to partners
European ambition
→ THE EUROPEAN SPACE AGENCY

Moon Missions/Elements Study Candidates

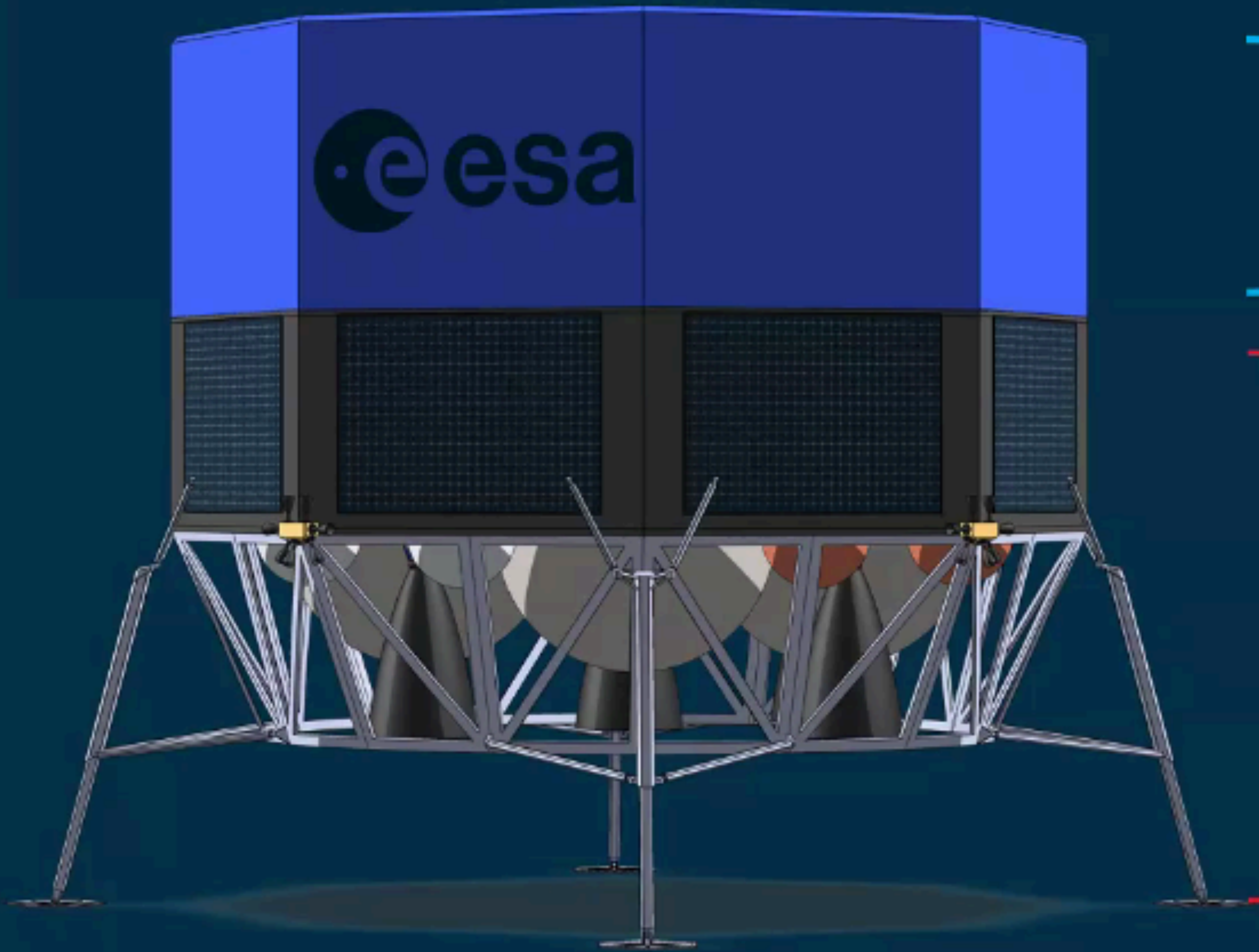
- *Cargo Logistic Mission (CDF study completed on Cargo CPE, pre-Phase A with Primes)*
- *POLESTAR (CDF study completed)*

- **Polar Explorer Mission (CDF study completed, pre-Phase A with Primes)**
- **Astrophysical Lunar Observatory (ALO) Mission (CDF study completed)**
- **Bioscience on the Moon Mission (CDF study completed)**
- Geology Mission (CDF study planned 2022)

- **European Charging Station for the Moon (CDF study completed, pre-Phase A in preparation)**
- **European Moon Rover System (EMRS) (Pre-Phase A ongoing)**
- Versatile Mobility Platform & Habitation
- ISRU Pilot Plant Mission (CDF study complete in 2018, new CDF study planned in 2022)

Preparing enabling infrastructure and capabilities

European Large Logistics Lander

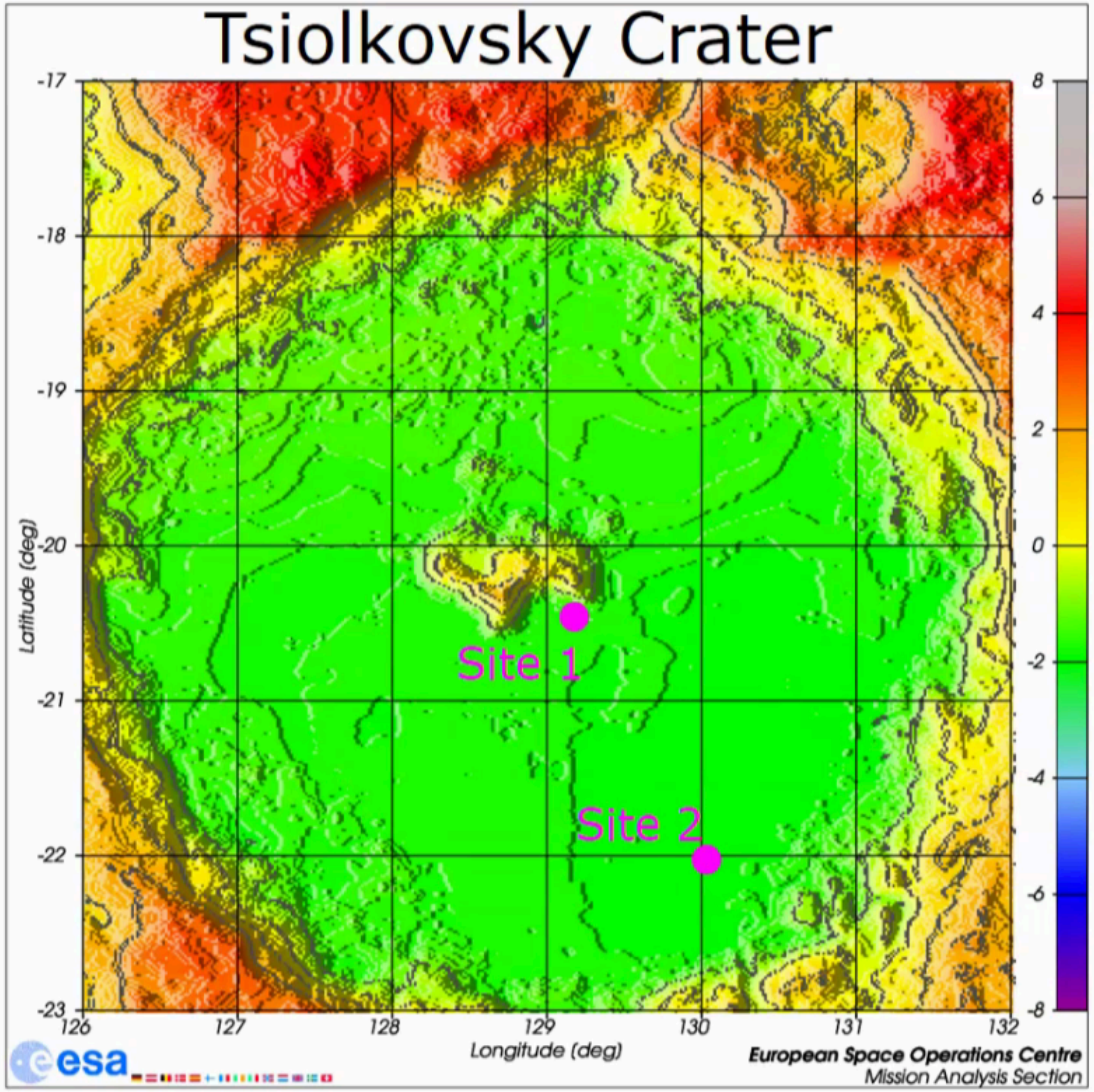


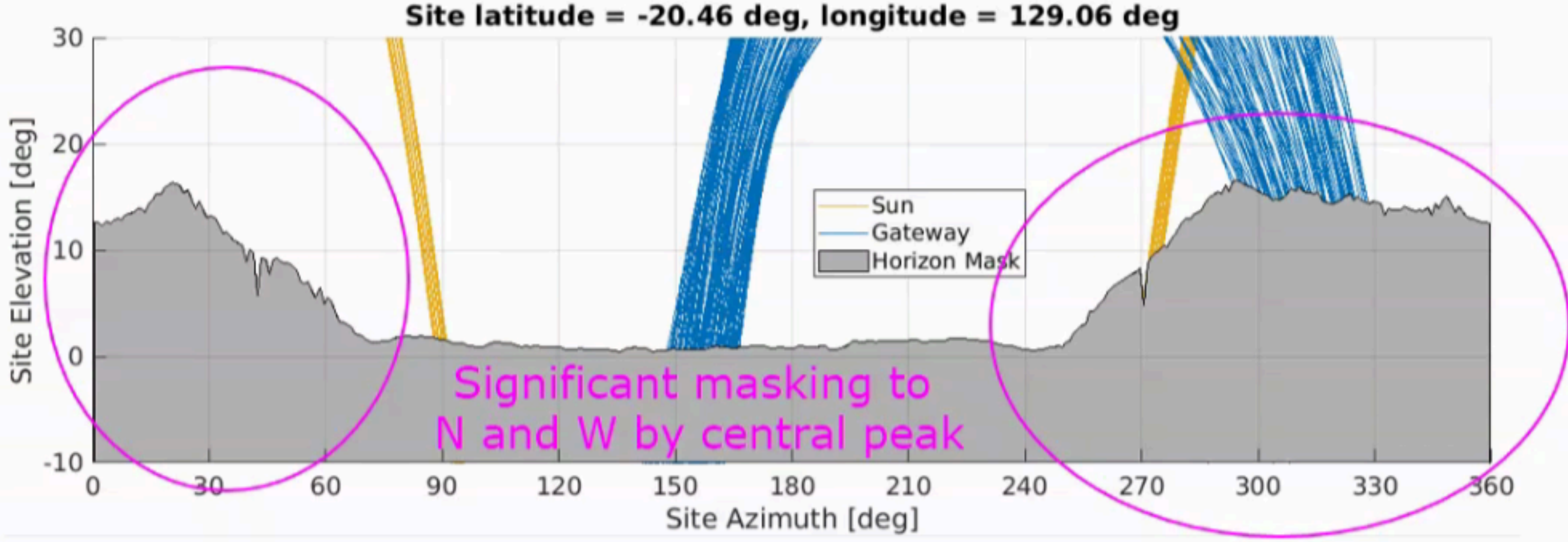
Payload/cargo = customer

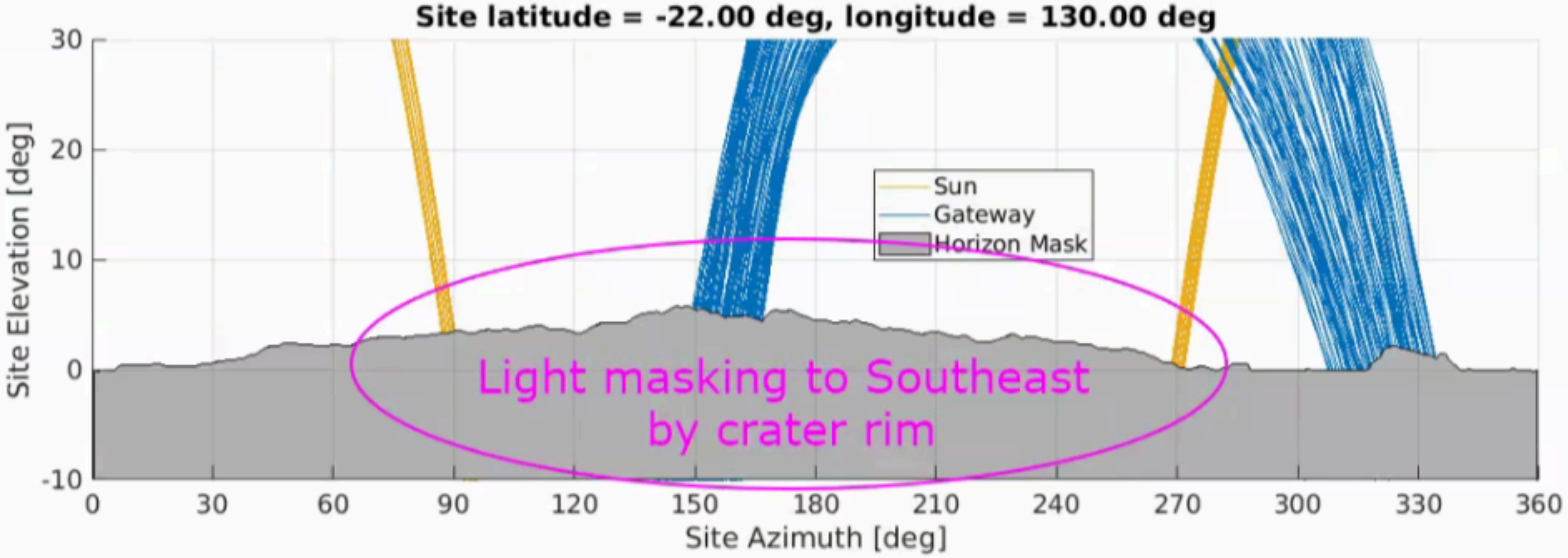
CPE (Cargo Platform Element)= Interface between customer and LDE + specific services to customer

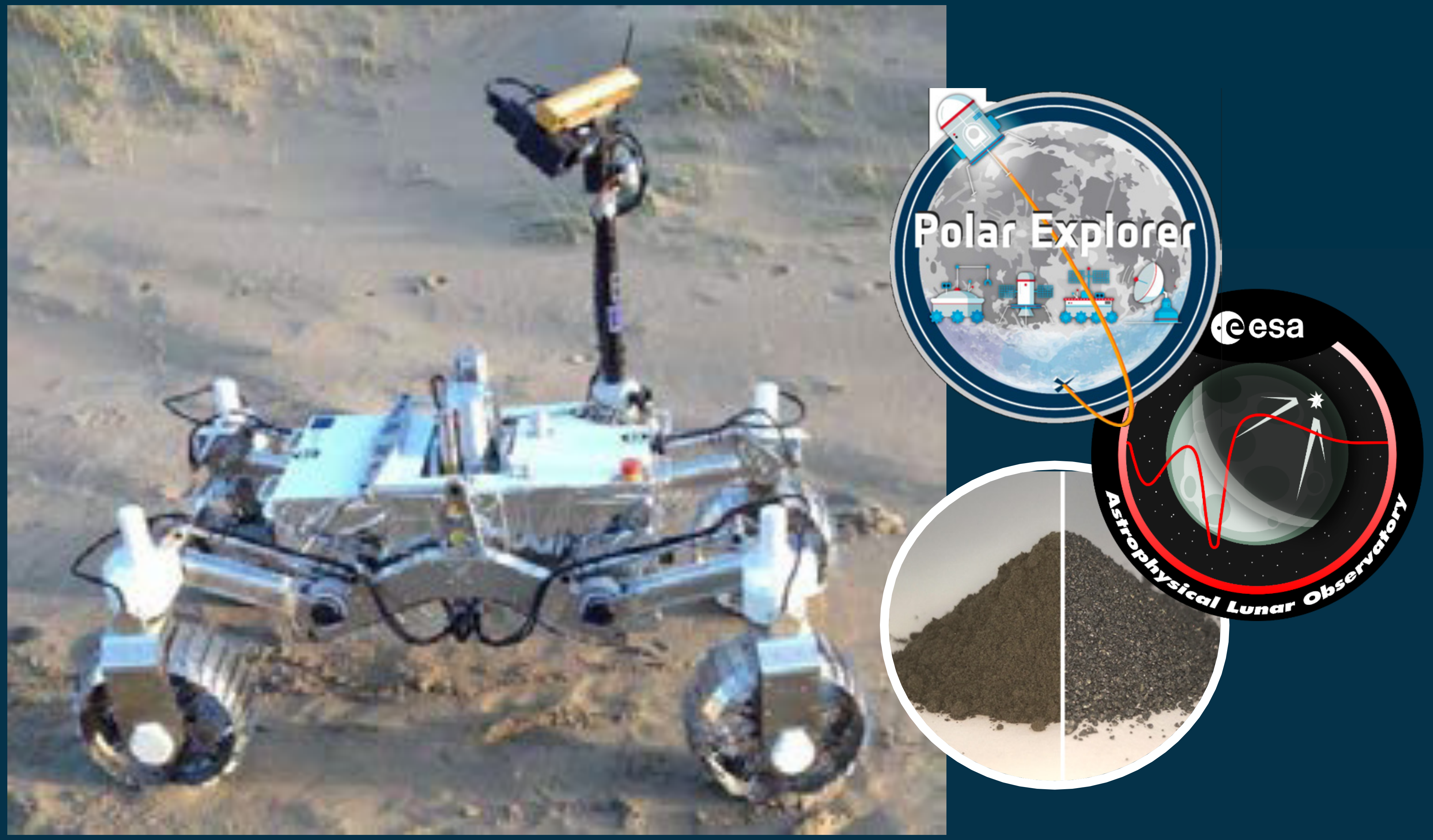
Lander Descent Element (LDE) = Recurring Element

Horizon Masks: Optimise the Landing Location









Description

- Multi-purpose modular mobility solution for future EL3 mission concepts requiring rover element:
  - Polar Explorer (science rover)
  - ALO (antenna deployment)
  - ISRU Pilot Plant (excavator rover)
- Mobility class of few hundreds of kg
- Precursors ground demonstrations using challenge-based innovation to attract non-space industry SMEs, start-ups, incl. in smaller participating states

European Moon Rover System (EMRS)

Technology

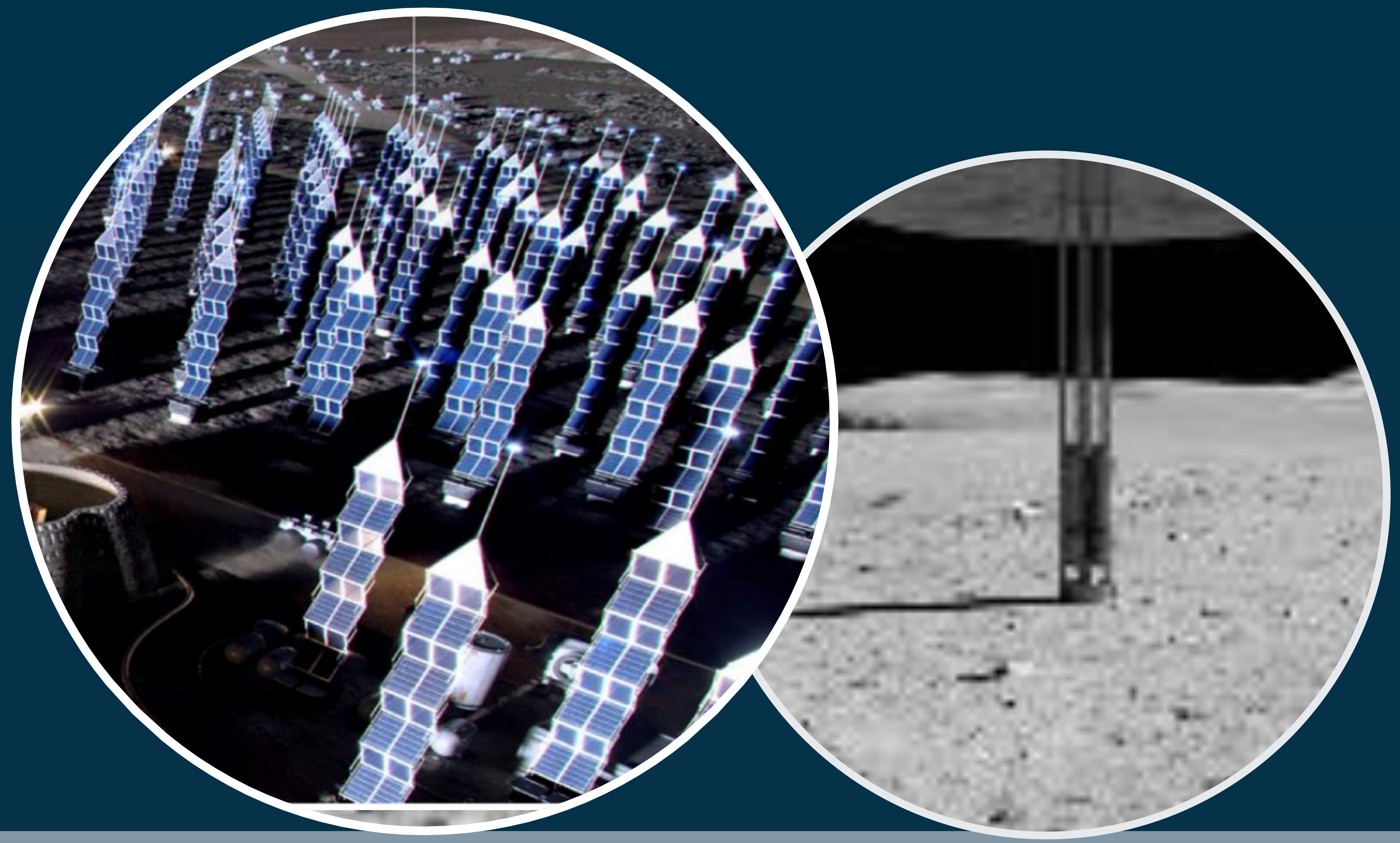
- Surface mobility considered key for planetary exploration
- Built on ExoMars/SFR rover heritage
- Technology maturation themes (e.g.):
  - Locomotion
  - Power, thermal & night survival
  - Communications & Navigation
  - Robotics
  - Dust resilience, etc.

Science

- Science instrumentation based on mission concept
- Closure of knowledge gaps around surface mobility and exploration in lunar environment

Schedule

- Pre-Phase A
  CDF (PE, ALO) completed in 2020/21
  Ongoing pre-phase A in 2022
- Potential Phase A/B1
  Advanced rover study in parallel to EL3 and payload developments in P3
  (possibility to be provided / co-developed by national agencies)



Description

- EL3 based surface power station based on photovoltaics and RFCS system, possibly mini-nuclear reactor
  - ❖ Local power element for robotic and human surface activities
  - ❖ Potential contribution to Artemis surface architecture (or for other partners)
  - ❖ Communication (to Earth, Relay Orbiter, Surface network) as additional service

European Charging Station for the Moon

Technology

- Technology maturation for power generation and storage subsystems
  - RFCS technology
- Leverage heritage and industrial capacity for solar power satellites
- Investigate technologies for use power charging
- Wireless power transfer demonstration

Science

- SciSpacE strategy is in development.
- Applied sciences investigations
- Other opportunistic science

Schedule

- PrePhase A
  CDF completed in 2021
  Pre-phase A planned In 2022
- Potential Phase A/B1
  Study to mature infrastructure concept and interfaces starting in 2023
- Potential Phase B2-C/D
  Implementation decision at CM25+

Description

- Scale and demonstrate lunar oxygen production from regolith, building on ISRU demo and ground based work
- Potential contribution to Artemis base camp (or other partners), potentially including excavation rover
- Secure roles for European industries in space resources market

ISRU Pilot Plant

Technology

- Technology maturation for ISRU processing (e.g. sounding, drilling, excavation, characterisation, processing), incl. ground prototypes
- Advancement of mobile excavation rover

Science

- SciSpacE strategy is in development.
- Science investigations could look at:
  - resource characterisation and interaction with the environment
  - Applied sciences related to sustainability
  - Investigation of biosystem integration in mining and processing

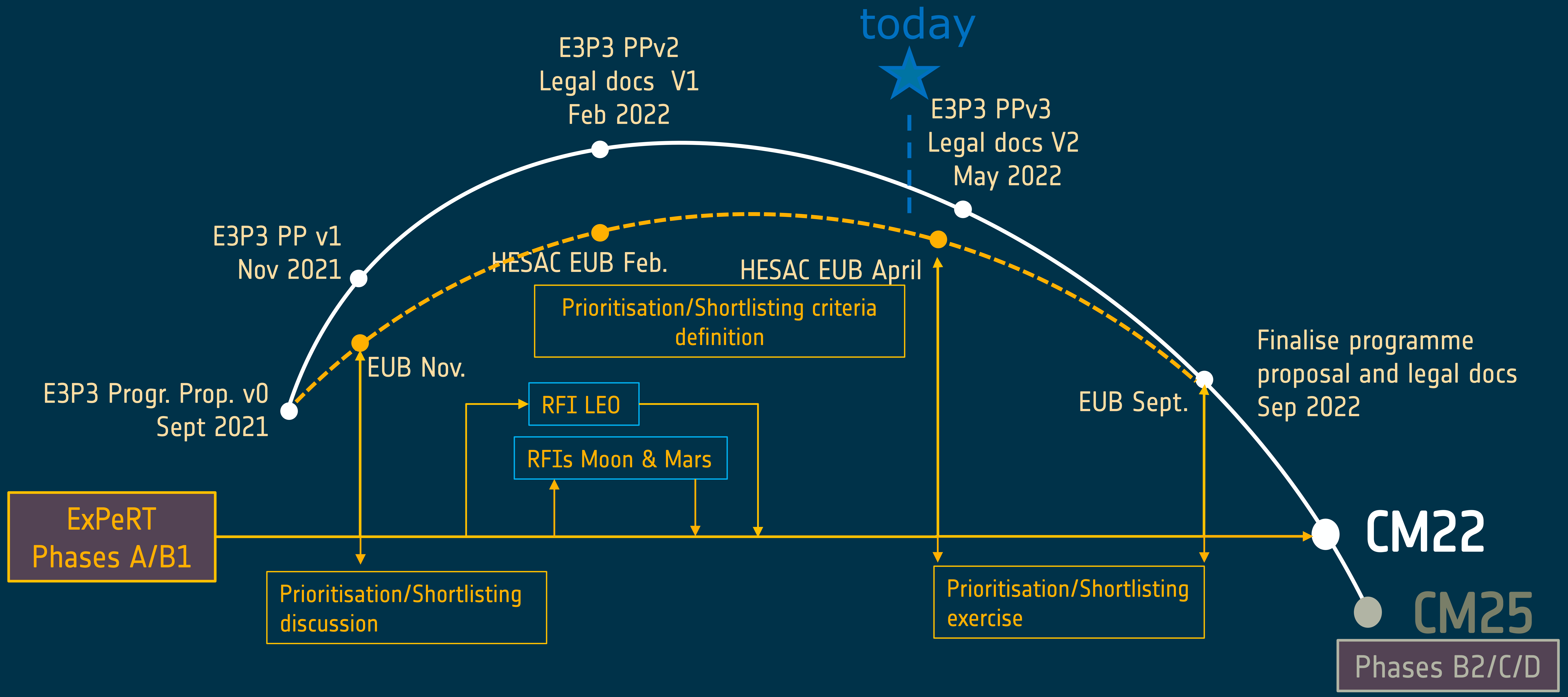
Schedule

- PrePhase A
  CDF completed in 2018 (old concept)
  CDF update planned in 2022
- Potential Phase A/B1
  Study to mature infrastructure concept and interfaces starting in 2023
- Potential Phase B2-C/D
  Implementation decision at CM25+

Phase A/B1 Studies in Period 3

Note: A notional process flow is shown.

Roadmap CM22 – European Exploration Envelope Programme (E3P3)



EUB = European Utilisation Board (Delegation level)

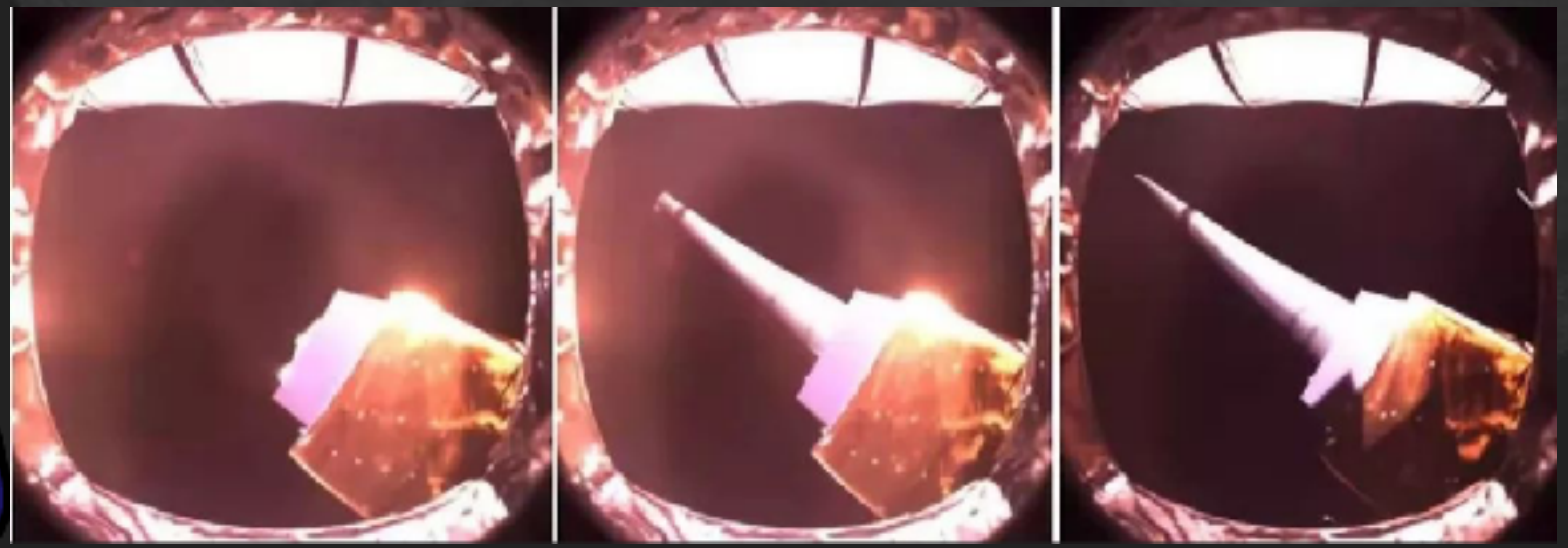
OBJECTIVES OF THE ALO TOPICAL TEAM

- Define the science objectives
- Define the scientific requirements
- Coordinate the technology developments

RADBOUD RADIO LAB

preDEX
PRECURSOR DARK AGES EXPLORER

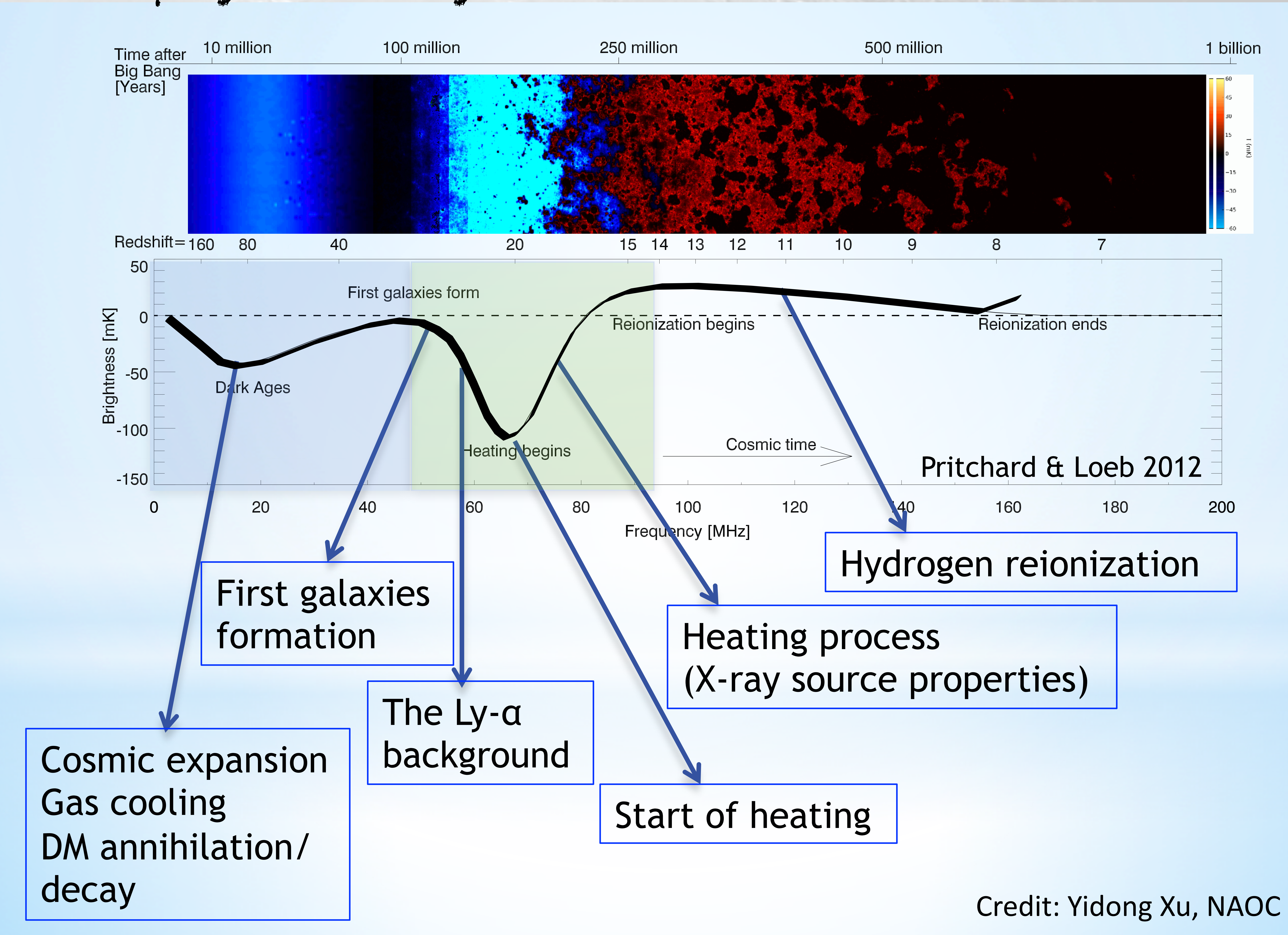
esa
Astrophysical Lunar Observatory



EXPECTED 21 CM GLOBAL SIGNAL FROM STANDARD MODELS

Interplay between Hydrogen and "the rest of the Universe"

Dark Ages



Cosmic Dawn

Credit: Yidong Xu, NAOC

UNIQUE SCIENCE FROM THE MOON

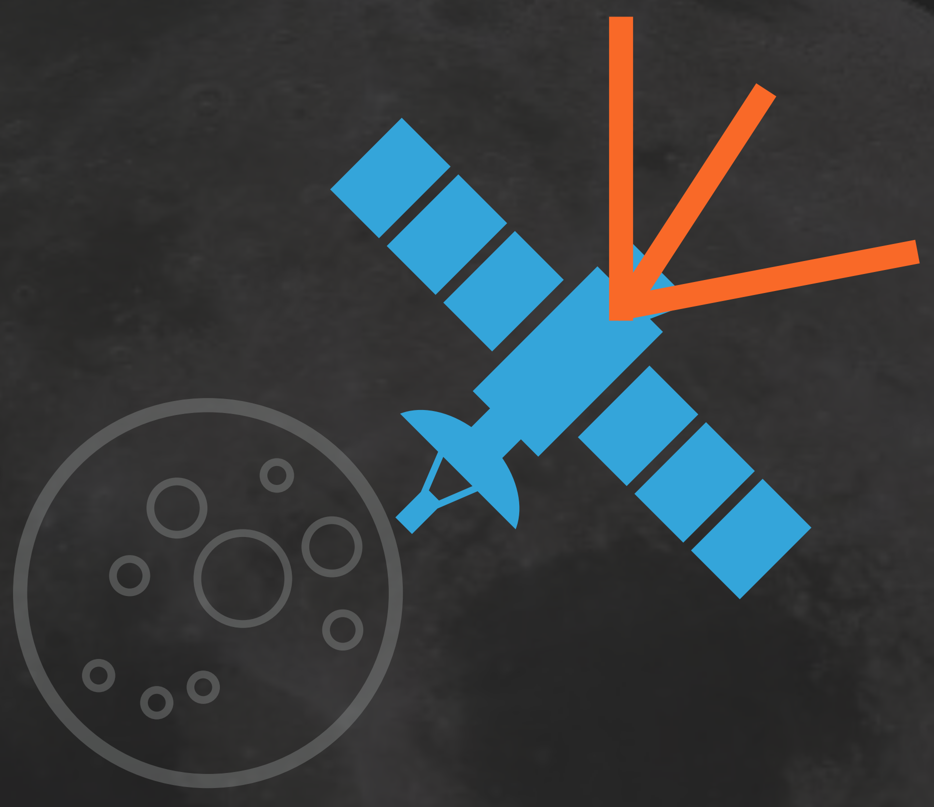
SCIENCE & SCALABILITY

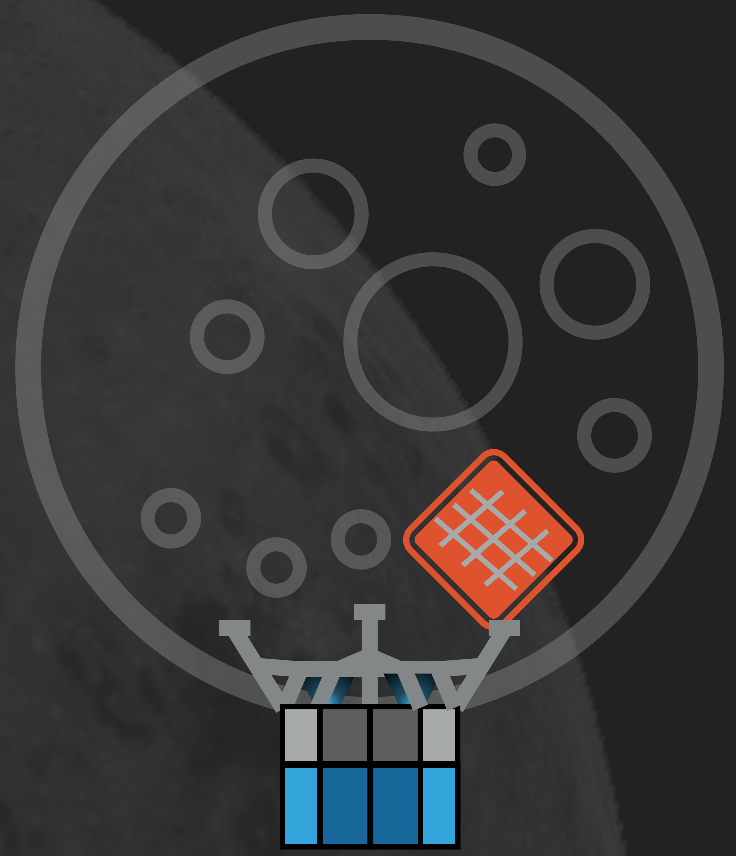
Number of antennas - Array concept	Global Dark Ages signal (DA)	Global Cosmic Dawn signal (CD)	Dark Ages Power Spectra	Dark Ages Tomography	Cosmic Dawn Power spectra	Cosmic Dawn Tomography
1	For z = 80 (17.5 MHz), bandwidth 10 MHz, deltaT = 10 mK: t_int = 2000 hours.	For z = 20 (70 MHz), bandwidth 1 MHz, deltaT = 10 mK: t_int = 17 hours.	N/A	N/A	N/A	N/A
2	For z = 80 (17.5 MHz), bandwidth 10 MHz, deltaT = 10 mK: t_int = 1400 hours.	For z = 20 (70 MHz), bandwidth 1 MHz, deltaT = 10 mK: t_int = 12 hours.	N/A	N/A	N/A	N/A
3 (all outriggers)	For z = 80 (17.5 MHz), bandwidth 10 MHz, deltaT = 10 mK: t_int = 1150 hours.	For z = 20 (70 MHz), bandwidth 1 MHz, deltaT = 10 mK: t_int = 10 hours.	N/A	N/A	N/A	N/A
4 (all outriggers)	For z = 80 (17.5 MHz), bandwidth 10 MHz, deltaT = 10 mK: t_int = 1000 hours.	For z = 20 (70 MHz), bandwidth 1 MHz, deltaT = 10 mK: t_int = 8.5 hours.	N/A	N/A	N/A	N/A
4 x 4	N/A	N/A	S/N << 1	TBD	S/N > 1 for z = 20, k from 0.003 to 0.1 (see plot 1 in the 'sensitivity plots' tab)	TBD
8 x 8	N/A	N/A	S/N << 1	TBD	S/N > 1 for z = 22, k from 0.003 to 0.1 (see plot 2 in the 'sensitivity plots' tab)	TBD
16 x 16	N/A	N/A	S/N << 1	TBD	S/N > 1 for z = 22, k from 0.003 to 0.2 (see plot 3 in the 'sensitivity plots' tab)	TBD
32 x 32	N/A	N/A	S/N << 1	TBD	S/N > 1 for z = 25, k from 0.003 to 0.1 (see plot 4 in the 'sensitivity plots' tab)	TBD
64 x 64	N/A	N/A	S/N << 1	TBD	S/N > 1 for z = 27, k from 0.003 to 0.1 (see plot 5 in the 'sensitivity plots' tab)	TBD
128 x 128	N/A	N/A	S/N << 1	TBD	S/N > 1 for z = 28, k from 0.003 to 0.1 (see plot 6 in the 'sensitivity plots' tab)	TBD

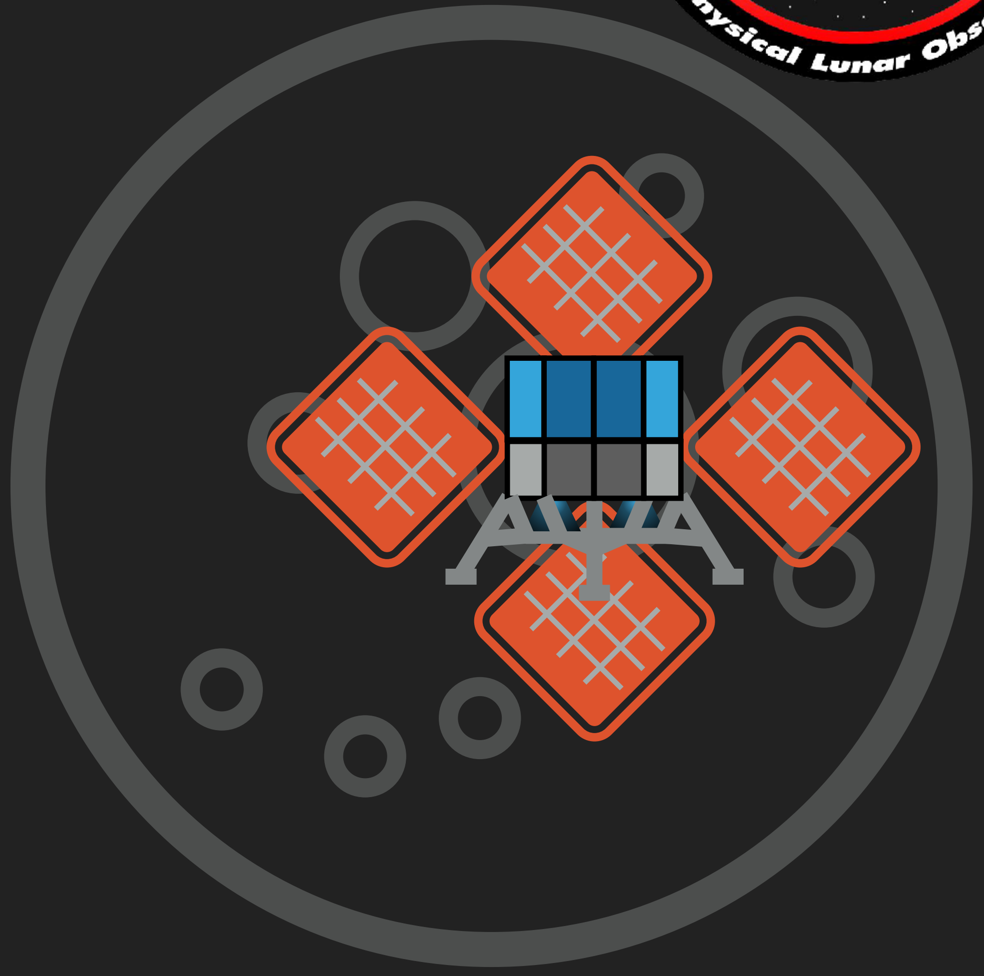
ASTRONOMICAL LUNAR OBSERVATORY

TECHNOLOGY ROADMAP

Towards an array on the moon







2022	June 10 2022	July 2022	Nov 2022	2025	2029	2035?
ALO TT & CDF PreDEX Pre-Phase A	ALO Roadmaps Draft	ALO Roadmaps	ESA Ministerial	MoonLight Demonstrator (ESA): Technology demonstrator	South Pole mission: ALO pre-cursor	Far side mission: ALO array
		Pre-Phase A studies		Miniaturised electronics RFI, EMC mitigation techniques Data processing	Printed antennes Deployment Interaction with Lunar Regolith Interferometry in space Distributed data processing	

Some scaled budgets for illustration

ONLY TO ILLUSTRATE ORDERS OF MAGNITUDE

Array Size	Antennas Mass* [t]	Hubs Mass** [t]	Harness Mass [t]	Station Mass [t]	Total Mass*** [t]	Data rate **** [kbps]
4x4=16	**0.03**	**0.05**	**0.01**	**0.50**	**0.98**	**0.6**
8x8=64	*0.12*	*0.20*	*0.03*	*0.69*	*1.43*	*5*
16x16=256	*0.5*	*0.8*	*0.1*	*1.4*	*3.2*	*40*
32x32=1024	**1.9**	**3.2**	**0.5**	**4.5**	**10.5**	**300**
64x64=4096	*7.6*	*12.9*	*2.2*	*16.6*	*39.7*	*2,400*
128x128=16384	**30.3**	**51.6**	**10.2**	**65.4**	**157.8**	**19,500**

Number of Hubs = Number of Antennas / 16
* Single antenna dipole mass: ~2kg
** Single hub mass w/o antennas or harness: ~50kg
*** Includes rover ~400kg
**** Only for imaging experiment array (global detection experiment is 1,000 kbps/antenna)
NOTE: Expected downlink capability < 25-50 Mbps

Baseline is 4*4 - exploring technology developments to go to 32*32 or 128*128

TECHNOLOGY DEVELOPMENTS

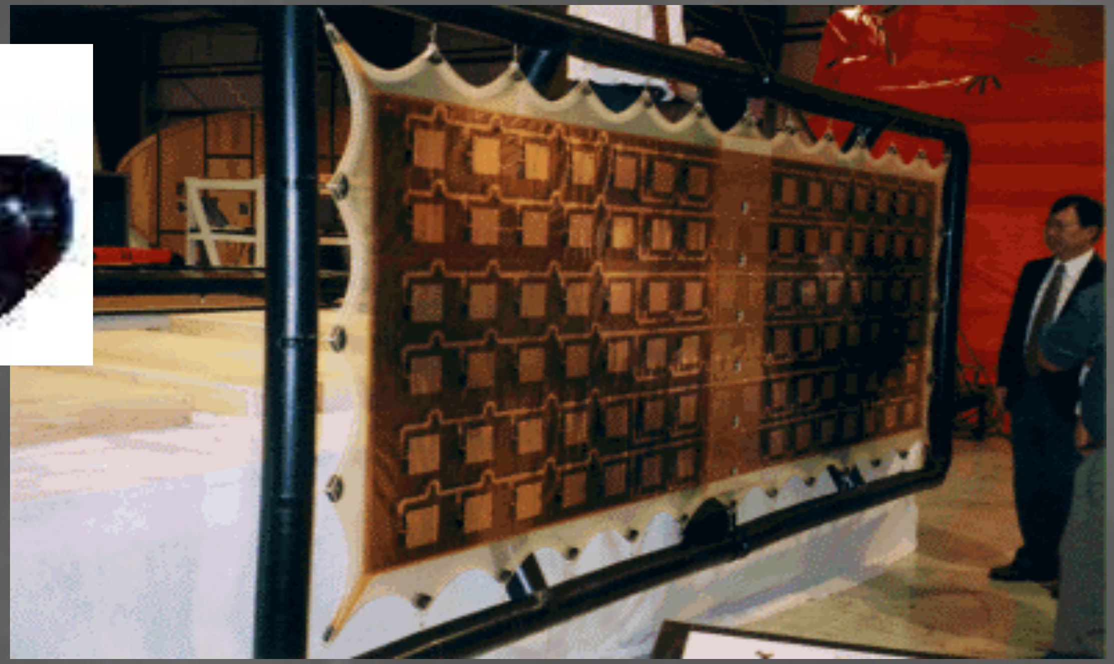
What can be done in the scope of the ALO TT?

- Within the ALO scope there are certain developments we can push for, and others that we should follow.
- Technology developments on wireless/optical communication, solar panel technologies & other power solutions (also for night survival), robotics are also happening outside the scope of ALO, these should be identified and followed.
  - In ALO we should push for optimisation of mass - power - data via the developments on the:
    - Antenna;
    - LNA (analogue electronics);
    - Receiver (digital electronics);
    - Data processing architecture (distributed data processing).
- Focus on inflatables and integration off the antenna systems and electronics, and possibly power generation.

TECHNOLOGY DEVELOPMENTS

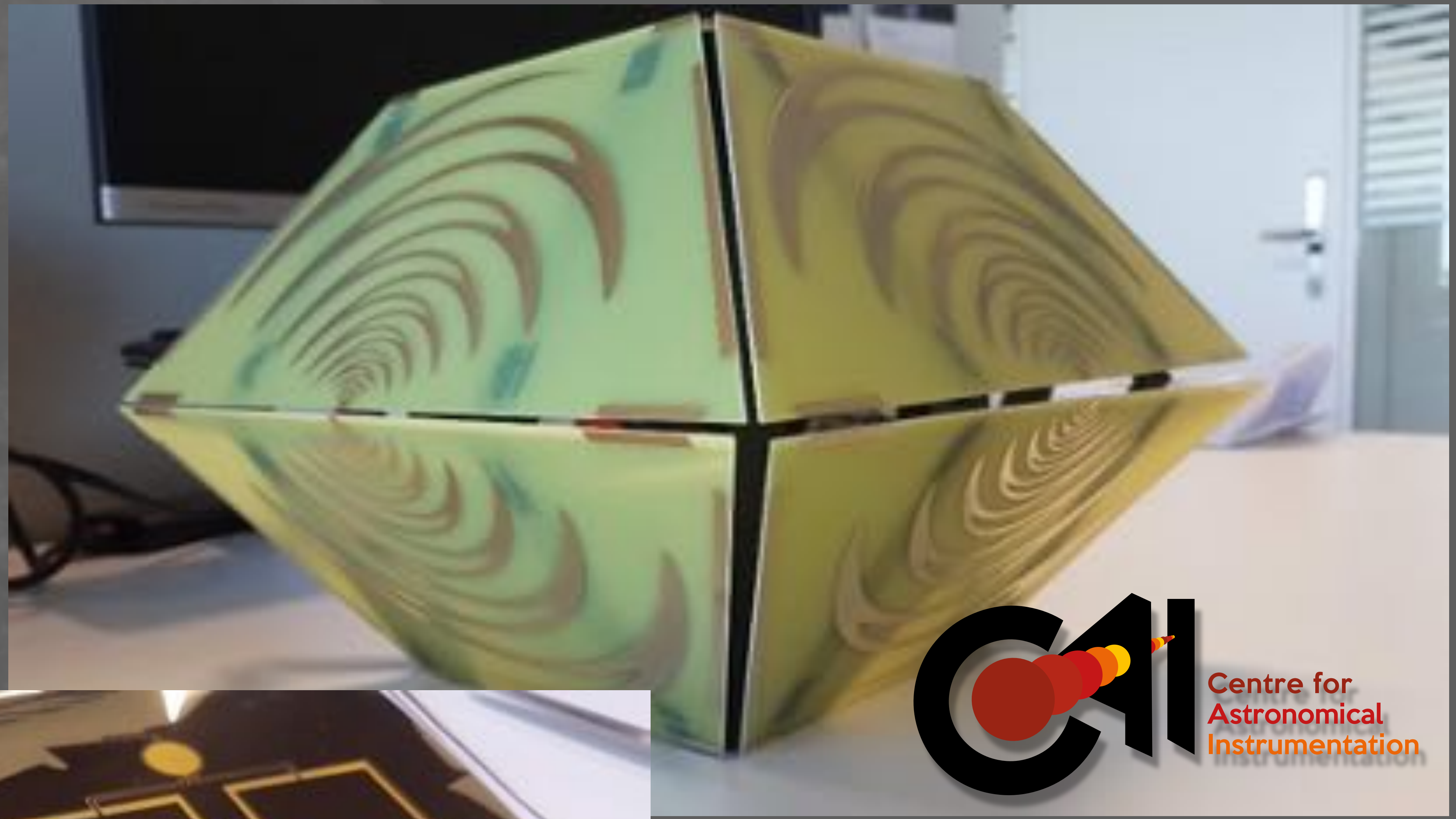
Optimisation of Mass - Power - Data: printed antennas & Inflatable structures

Roll-up Antenna (stowed)

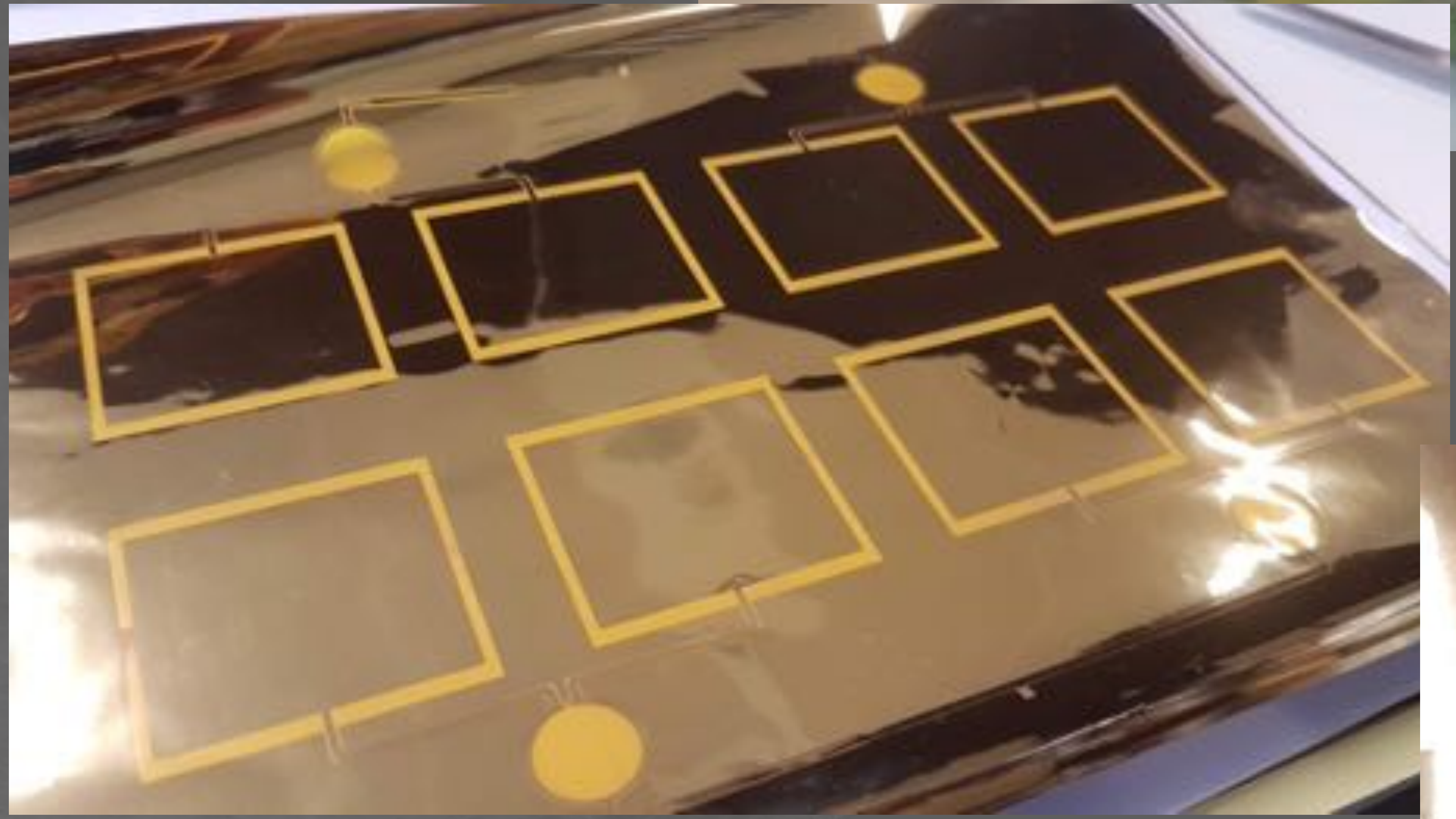


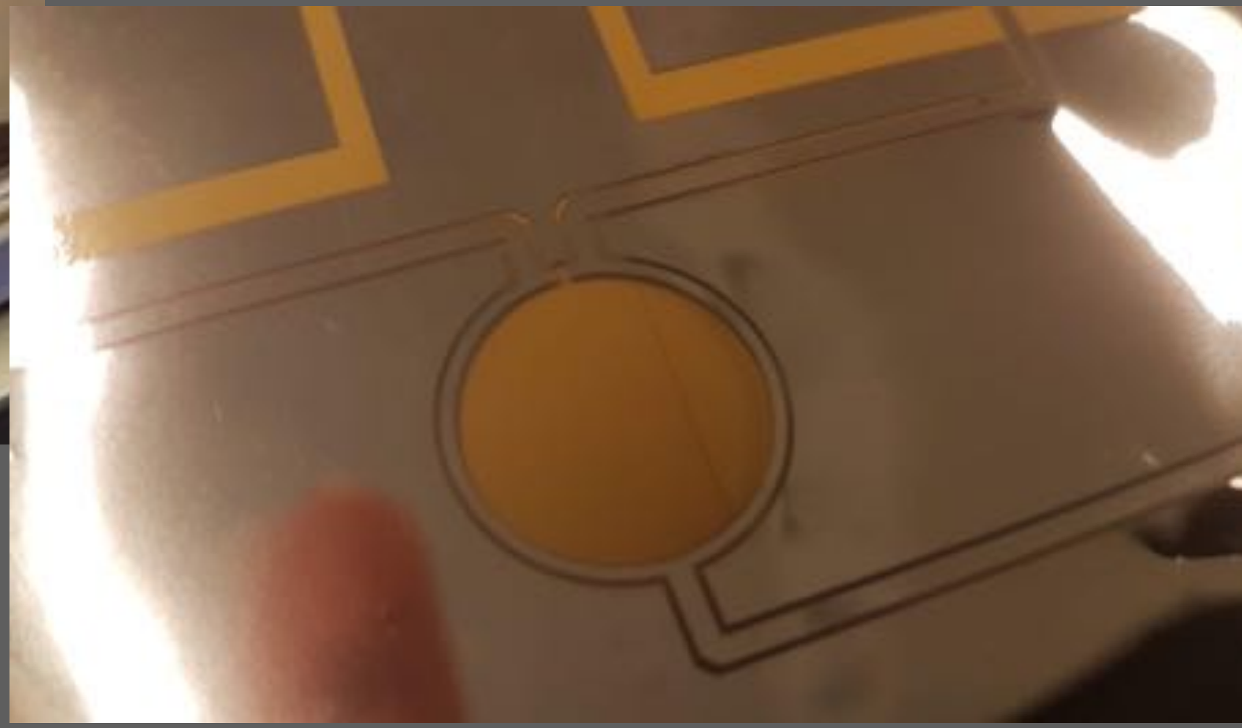
Fully Deployed Antenna

JPL Design



ASTRON Design



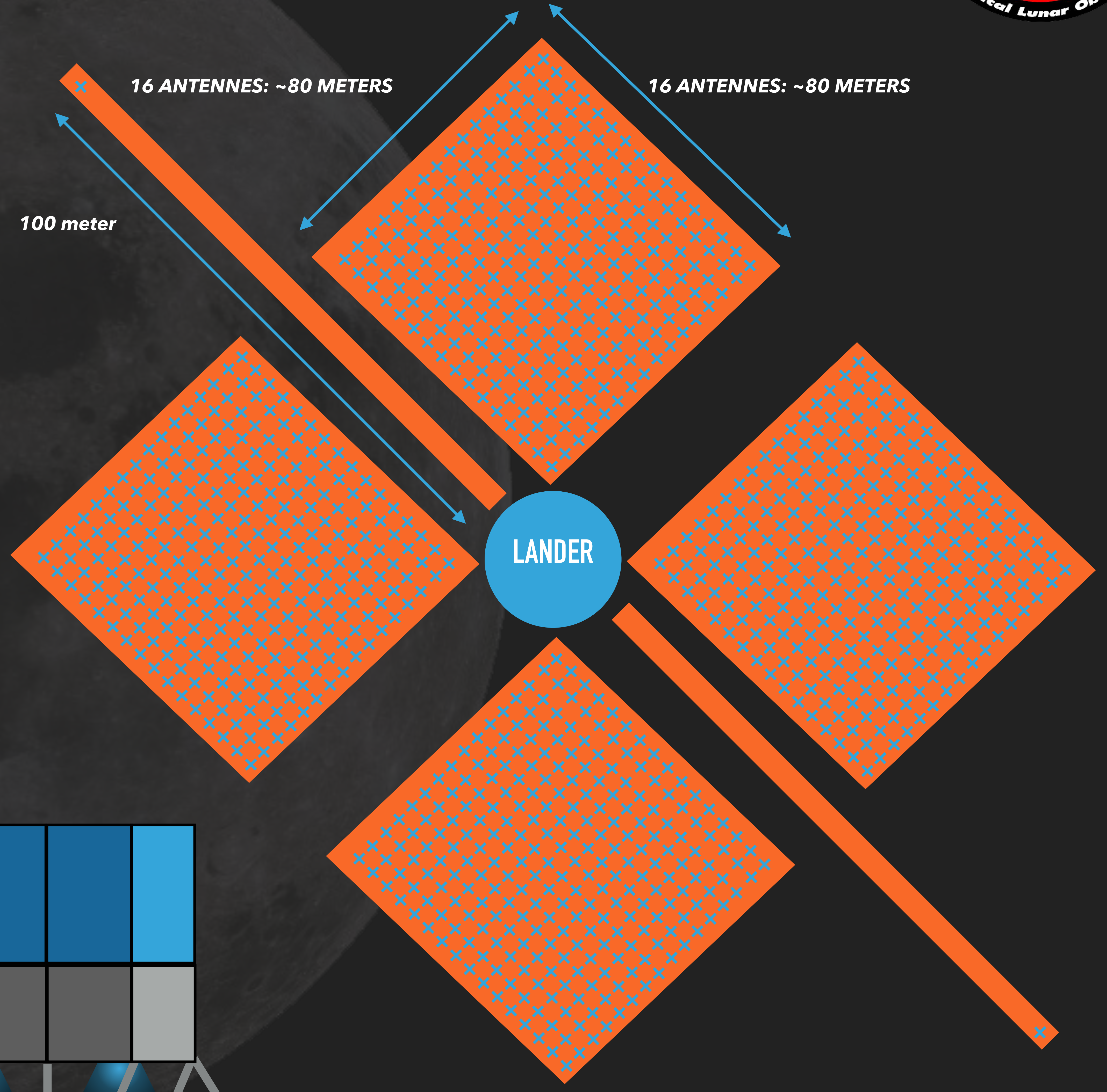


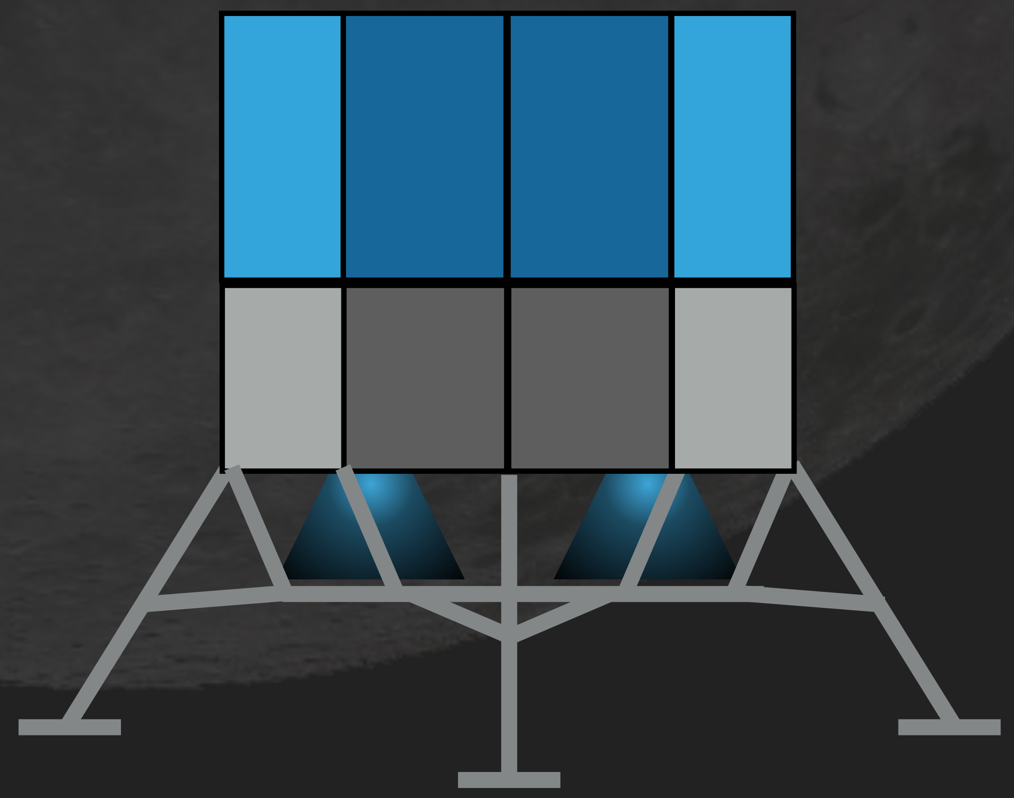
TUe - CAI Design: inflatable antenna
test at a balloon this year

FUTURE CONCEPT?

Provisional concept

- 5 meter long crossed dipoles printed on Kapton
- **To allow more science: 32 * 32=1024 (minimal) or 128*128=16384 (ideal) antennas**
- Inflatable kapton "air-mattress"
- No rover, scalable, deployment and regular distribution **combined** in one solution
- One antenna concept for all science
- Further integration:
  - Analogue & Digital Electronics?
  - Solar panels printed on Kapton?





INTERNATIONAL LUNAR OBSERVATORY

INTERNATIONAL COLLABORATION ON SCIENCE EXPLORATION ON THE MOON

- OBJECTIVE:
  - LONG-TERM: WORK TOWARDS ONE COMMON DESIGN, BUILD THE ARRAY FROM MULTIPLE LAUNCHES BY INDIVIDUAL PARTNERS
  - SHORT-TERM: IDENTIFY AND COLLABORATE ON TECHNOLOGY DEVELOPMENTS
  - LIKE ALMA AND SKA